

PROGRESS/STATUS REPORT
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This Research Grant provides support for development of nanotechnology for x-ray astronomy instrumentation. MIT has made significant progress in several development areas.

In the last year we have made considerable progress in demonstrating the high-fidelity patterning and replication of x-ray reflection gratings. We developed a process for fabricating blazed gratings in silicon with extremely smooth and sharp sawtooth profiles, and developed a nanoimprint process for replication. We also developed sophisticated new fixturing for holding thin optics during metrology without causing distortion. We developed a new image processing algorithm for our Shack-Hartmann tool that uses Zernike polynomials. This has resulted in much more accurate and repeatable measurements on thin optics.

Publications:

- R118. "Constellation-X Spectroscopy X-ray Telescope (SXT)," R. Petre, W.W. Zhang, D.A. Content, T. T. Saha, J. Stewart, J.H. Hair, D.Nguyen, W.A. Podgorski, W.R. Davis, Jr., M.D. Freeman, L.M. Cohen, M.L. Schattenburg, R.K. Heilmann, Y. Sun and C. Forest, *Proc. SPIE 4851, X-ray and Gamma-ray Telescopes and Instruments for Astronomy* (SPIE, Bellingham, WA), eds. J.E. Truemper and H.D. Tananbaum, 433-440 (2003).
- R119. "Constellation-X Spectroscopy X-ray Telescope assembly and alignment," W.A. Podgorski, D.A. Content, J.H. Hair, R. Petre, T.T. Saha, M.L. Schattenburg, J. Stewart and W.W. Zhang, *Proc. SPIE 4851, X-ray and Gamma-ray Telescopes and Instruments for Astronomy* (SPIE, Bellingham, WA), eds. J.E. Truemper and H.D. Tananbaum, 491-502 (2003).
- R120. "Precision shaping, assembly and metrology of foil optics for x-ray reflection gratings," C.R. Forest, M.L. Schattenburg, C.G. Chen, R.K. Heilmann, P. Konkola, J. Przybylowski, Y. Sun, J. You, S.M. Kahn and D. Golini, *Proc. SPIE 4851, X-ray and Gamma-ray Telescopes and Instruments for Astronomy* (SPIE, Bellingham,

- WA), eds. J.E. Truemper and H.D. Tananbaum, 538-548 (2003).
- R121. "Constellation-X soft x-ray telescope segmented optic assembly and alignment implementation," J.H. Hair, J. Stewart, R. Petre, W.W. Zhang, D.A. Content, T.T. Saha, W.A. Podgorski, P.E. Glenn, M.L. Schattenburg, R.K. Heilmann, Y. Sun and G. Nanan, *Proc. SPIE* **4851**, *X-ray and Gamma-ray Telescopes and Instruments for Astronomy* (SPIE, Bellingham, WA), eds. J.E. Truemper and H.D. Tananbaum, 696-707 (2003).
- R122. "Nanometer-accurate grating fabrication with scanning beam interference lithography," C.G. Chen, P.T. Konkola, R.K. Heilmann, C. Joo and M.L. Schattenburg, *Proc. SPIE* **4936**, *Nano- and Microtechnology: Materials, Processes, Packaging, and Systems* (SPIE, Bellingham, WA), ed. D.K. Sood, 126-134 (2003).
- R123. "Spatial phase locking with shaped beam lithography," J.G. Hartley, T.R. Groves, H.I. Smith, M.K. Mondol, J.G. Goodberlet, M.L. Schattenburg, J. Ferrera and A. Bernshteyn, *Rev. Sci. Instrum.* **74**, 1377-1379 (2003). (*CSR Reprint 01-86*)
- R124. "Fabrication of saw-tooth diffraction gratings using nanoimprint lithography," C.-H. Chang, R.K. Heilmann, R.C. Fleming, J. Carter, E. Murphy, M.L. Schattenburg, T.C. Bailey, R.D. Frankel and R. Voisin, *J. Vac. Sci. Technol. B* **21**, 2755-2759 (2003).
- R125. "Precision microcomb design and fabrication for x-ray optics assembly," Y. Sun, R.K. Heilmann, C.G. Chen, C.R. Forest and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **21**, 2970-2974 (2003).
- R126. "Nanometer-level repeatable metrology using the Nanoruler," P. Konkola, C. Chen, R.K. Heilmann, C. Joo, J. Montoya, C.-H. Chang and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **21**, 3097-3101 (2003).
- P127. "Thin glass optic and silicon wafer deformation and kinematic constraint," C. Forest, M. Akilian, G. Vincent, A. Lamure and M.L. Schattenburg, *Proc. of the 18th Annual Meeting of the American Society for Precision Engineering*, **30** (ASPE, Raleigh, NC) 39-42 (2003).
- R128. "Metrology of thin transparent optics using Shack-Hartmann wavefront sensing," C.R. Forest, C.R. Canizares, D.R. Neal, M. McGuirk, A.H. Slocum and M.L. Schattenburg, *J. Optical Engineering* **43**, 742-753 (2004).
- P129. "Grating arrays for high-throughput soft x-ray spectrometers," A.P. Rasmussen, A. Aquila, J. Bookbinder, C. Chang, E. Gullikson, R.K. Heilmann, S.M. Kahn, F. Paerels and M.L. Schattenburg, *Proc. SPIE* **5168**, *Optics for EUV, X-ray, and Gamma-ray Astronomy* (SPIE, Bellingham, WA), eds. O. Citterio and S.L. O'Dell, 248-259 (2004).
- P130. "Advances in reflection grating technology for Constellation-X," R.K. Heilmann, M. Akilian, C.-H. Chang, C.G. Chen, C. Forest, C. Joo, P. Konkola, J.C. Montoya, Y. Sun, J. You and M.L. Schattenburg, *Proc. SPIE* **5168**, *Optics for EUV, X-ray, and Gamma-ray Astronomy* (SPIE, Bellingham, WA), eds. O. Citterio and S.L. O'Dell, 271-282 (2004).
- P132. "Dimensional metrology for nanometer-scale science and engineering: towards sub-nanometer accurate encoders," R.K. Heilmann, C.G. Chen, P.T. Konkola and M.L. Schattenburg, *Nanotechnology* **15**, S504-S511 (2004).
- P133. "High fidelity grating replication using thermal nanoimprint lithography," C.-H. Chang, J.C. Montoya, M. Akilian, A. Lapsa, R.K. Heilmann, M.L. Schattenburg,

- P276. "Advances in x-ray reflection grating technology," M. Akilian, C.-H. Chang, R. Heilmann, J. Montoya and M.L. Schattenburg, *Constellation-X Mission Facility Science Team Meeting*, NASA Goddard Space Flight Center, Greenbelt, Maryland, Oct. 14-15, 2004.
- P277. "Thin optics constraint," M. Akilian, C. Forest, A. Slocum, D. Trumper and M.L. Schattenburg, *19th Annual Meeting of the American Society of Precision Engineering*, Orlando, Florida, Oct. 24-29, 2004 (*Poster 2, Equipment, Machines & Instruments - Design & Testing*).
- P278. "Measuring two-axis stage mirror non-flatness using linear/angular interferometers," J. Montoya, R. Heilmann and M.L. Schattenburg, *19th Annual Meeting of the American Society of Precision Engineering*, Orlando, Florida, Oct. 24-29, 2004 (*Poster 5, Metrology - Analysis & Modeling*).
- P279. "Metrology for nanometer scale lithography," M.L. Schattenburg and R.K. Heilmann, *Materials Research Society Symposium on Progress in Semiconductor Materials IV — Electronic and Optoelectronic Applications*, Boston, Massachusetts, Nov. 30, 2004 (*invited paper C3.4*).

Master's Theses:

- TM10. Chulmin Joo, *Image Grating Metrology using a Fresnel Zone Plate*, Master's Thesis, Department of Mechanical Engineering, Aug. 2003.
- TM11. Chih-Hao Chang, *Fabrication of Extremely Smooth Blazed Gratings*, Master's Thesis, Department of Mechanical Engineering, June 2004.
- TM12. Mireille K. Akilian, *Thin Optic Surface Analysis for High Resolution X-ray Telescopes*, Master's Thesis, Department of Mechanical Engineering, Sept. 2004.